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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2004/124

EXPERIMENTAL MEASUREMENT TO DETERMINE FINE DRY-BULB AND WET-BULB THERMOCOUPLE RESPONSE TIMES

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RELEASED BY:

DP Gleisner 20 Dec 2004

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REPORT DOCUMENTATION PAGE		Form Approved OMB No. 0704-0188
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1. REPORT DATE 20 December 2004	2. REPORT TYPE Technical Report	3. DATES COVERED July 2002
4. TITLE AND SUBTITLE Experimental Measurement to Determine Fine Dry-Bulb and Wet-Bulb Thermocouple Response Times		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Jonathan W. Kaufman, Ph.D. Kambiz Farahmand, Ph.D., Texas A&M University Katherine Stuble, St. Mary's College Coleen Chin, University of Maryland		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Air Warfare Center Aircraft Division Bldg. 2187, Suite 2280 48110 Shaw Road, Unit #5 Patuxent River, Maryland 20670-1906		8. PERFORMING ORGANIZATION REPORT NUMBER NAWCADPAX/TR-2004/124
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Air Systems Command 47123 Buse Road Unit IPT Patuxent River, Maryland 20670-1547		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

An experimental apparatus was built and used to measure the response time of very fine wet-bulb thermocouples in air. Rapid response solenoid valves (15 msec response time) were used to control airflow, through tubing into which wet-bulb thermocouples were placed. Thermocouple wire (type T, 0.005 cm diameter) was used to fabricate thermocouples for testing. The thermocouple tip (bead) was covered with a wick (cotton fiber) to build a wet-bulb. The experiment was performed for air velocities ranging from 1.50 to 2.5 m/sec, measured at the flow meter (0.166 – 0.478 m/sec) inside the housing and changes in temperature ranging from 12.5°C to 17.39°C wet-bulb. These experimental conditions were selected to simulate human respiratory conditions. The apparatus produced repeatable square waves and allowed change in direction of temperature gradient without difficulty. The experiment was carried out for both cooling (going from hot-to-cold) and heating (going from cold-to-hot) of the thermocouple using two different tubing diameter (1 and 1 5/16 in.).

Wet-bulb thermocouple response time of 0.175 sec (1 in. housing) and 0.153 sec (1 5/16 in. housing) were obtained. Conduction along thermocouple wire and radiation effects was shown to negligibly affect response times. The effect of the temperature change for small increments and direction of the gradient were also found to be insignificant. There was a negative correlation between air velocity and the time response of a wet-bulb thermocouple. This technique allows investigators a means of assessing data acquisition system response times in a repeatable fashion.

15. SUBJECT TERMS

wet-bulb temperature measurement, thermocouple, heat transfer, wet-bulb response time, convection, radiation, conduction

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Jonathan Kaufman, Ph.D.
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
Unclassified	Unclassified	Unclassified	SAR	38	342-8883

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

SUMMARY

An experimental apparatus was built and used to measure the response time of very fine wet-bulb thermocouples in air. Rapid response solenoid valves (15 msec response time) were used to control airflow, through tubing into which wet-bulb thermocouples were placed. Thermocouple wire (type T, 0.005 cm diameter) was used to fabricate thermocouples for testing. The thermocouple tip (bead) was covered with a wick (cotton fiber) to build a wet-bulb. The experiment was performed for air velocities ranging from 1.50 to 2.5 m/sec, measured at the flow meter (0.166 – 0.478 m/sec) inside the housing and changes in temperature ranging from 12.5°C to 17.39°C wet-bulb. These experimental conditions were selected to simulate human respiratory conditions. The apparatus produced repeatable square waves and allowed change in direction of temperature gradient without difficulty. The experiment was carried out for both cooling (going from hot-to-cold) and heating (going from cold-to-hot) of the thermocouple using two different tubing diameter (1 and 1 5/16 in.).

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INTRODUCTION

Measurement of instantaneous temperature changes in air or gas is becoming increasingly important in the field of heat transfer with numerous medical and scientific applications. Respiratory changes in air temperature in both human nasal and oral cavities require highly accurate and rapidly responding temperature sensors. The so-call lag test used in the past, consisting of rapid immersion of a dry-bulb thermocouple into a liquid bath was generally inadequate. Another problem was the difference in heat capacity of measured medium (air or water) considering that heat transfers faster in more dense, higher capacity medium. The biggest problem is repeatability from bath to bath because of differences in bath characteristics such as flow pattern, agitation rate, location and depth of the thermocouple, and film consistency. Usually when the thermocouple bulb or well is immersed into a bath, it was almost impossible to determine a true film coefficient.

In addition, the film coefficient is highly dependent on turbulence around the thermocouple tip, which is a function of fluid velocity. As turbulence increases, the fluid film thickness around the thermocouple tip decreases which in turn reduces response time by increasing the film coefficient, ASTM (reference 4). High liquid heat transfer coefficients help minimize thermocouple response time. However, this method appears to be inappropriate because of differences in the heat transfer mechanism when thermocouples are used in gas. Conduction is the primary heat transfer mechanism when using a liquid bath whereas both convection and radiation are the significant factors in gas media.

Table 1 published by OMEGA (reference 5) shows the relationship between air velocity and dry-bulb response time for fine type J thermocouples (no value reported for Type T thermocouple). These theoretical, not empirical, response times were computed for air temperatures between 37.8°C and 427°C and water temperatures between 37.8°C and 93.3°C by the manufacturer. No such data are published or reported for wet-bulb thermocouples. Considering the differences in density, heat capacity, and thermal conductivity, heat transfer properties at the thermocouple tip differ greatly in different media. Consequently, the use of a liquid model is inappropriate for determining response times in gas using a dry-bulb and most certainly not practical for determining wet-bulb time constants.

Table 1: Fine Thermocouple Response Times Reported by OMEGA (reference 5)

Wire Size (in.)	Still Air (msec)	60 ft/sec (msec)
.001	50	4
.005	1,000	80
.015	10,000	800
.032	40,000	3,200

When considering measurement of time constant in small conduits, others either did not measure it, see Webb (reference 1), or the techniques used in characterizing response times were unreliable, see Ray et al (reference 2). In an earlier study, Farahmand and Kaufman (reference 11) measured the response time of a dry-bulb thermocouple in air. The apparatus produced

repeatable square waves and allowed change in direction of temperature gradient without difficulty. The experiment was carried out for both cooling (going from hot-to-cold (H-C)) and heating (going from cold-to-hot (C-H)) of the thermocouple. This provided a suitable technique for measuring dry-bulb thermocouple time constants in air/gas medium for variety of temperature ranges with reliable and repeatable results. No comparable techniques for empirically determining response times of wet-bulb thermocouples are reported in the literature.

Considering the wet-bulb wick, any attempt to immerse the thermocouple in liquid bath would be ineffective. Manufacturers of thermocouples never attempted to quantify the response time for any type of wet-bulb thermocouples. One of the main obstacles in working with wet-bulb thermocouples is the problem with repeatability. This is because of variation in wick type, thickness, surface area of the thermocouple bead covered, and the level of moisture saturation of the wick covering the bead.

A methodology in making and maintaining robust wet-bulb thermocouples in both application and repeatability was developed and utilized (patent Number: 6659963) by Kaufman, Askew, and Farahmand (reference 12). The wet-bulb thermometers are basically dry-bulb thermocouples with a wick covering the tip or the measuring junction. The wick consists of 100% cotton string from nontreated, nonsterilized medical gauze tied around the tip of the thermocouple covering the bead. The number of the cotton fiber strands required to cover the bead will vary depending on the bead size. The cotton strands are also used to carry the water 1 cm or less from the end of the capillary tubing to the wick around the thermocouple bead. This assures that a water droplet is not formed around the thermocouple bead and yet the wick remains saturated with water.

METHODS

TEST APPARATUS

The apparatus which was used to determine the time constant for wet-bulb thermocouple uses a solenoid valve to switch between flow lines. Figure A-1 shows a schematic diagram of the experimental apparatus. The apparatus is also shown in figure A-2. Comparing several fast acting electrical solenoid valves currently available commercially (Cat series miniature valves, Sierra valves, Kloehn micro miniature valves, and others); Humphrey 310 in-line solenoid valve was selected. The Humphrey valve has a pressure rating from 0-125 psig and a temperature range of 0-50°C. The response time using 120 VAC (50/60 Hz), 4.5 watts is reported as 12/20 msec. Both DC and AC voltage valves have a energization time of 0.010 sec and a deenergization time 0.005 and 0.018 sec, respectively. Since an AC voltage valve was used for the experiment, the inlet flow lines were switched when changing flow temperatures to allow the valve to energize for all experimental runs. This minimized the valve response time to the lowest possible time and allowed consistency between runs.

The Humphreys solenoid valve was a 1/8 in. ported, two-position, three-way, single solenoid valve. The port configuration was either open or closed on one side. To optimize performance, large diameter clear Tygon tubing (R3603) was attached to the outlet port with ID = 1 5/16 in. and ID = 1 in. Tubing length was kept at minimum. The velocity conversion equations shown in table 2 were used to determine the air velocity in the two different size housing based on the three values of 1.5, 2.0, and 2.5 m/sec as measured by the flow meter.

Table 2: Velocity Conversions

Velocity Conversion	
$y = 0.11x + 0.001$	
Velocity measured by flow meter (m/sec)	Velocity in housing = 1 5/16 in. (m/sec)
1.5	0.166
2.0	0.221
2.5	0.276
$y = 0.1925x - 0.0031$	
Velocity measured by flow meter (m/sec)	Velocity in housing = 1 in. (m/sec)
1.5	0.28565
2.0	0.3819
2.5	0.47815

To stabilize flow rate and to minimize pressure drop in the system, two separate air compressors were used. The first compressor supplied the "ambient" flow line and the second compressor supplies air to the heated line. The air in this line was heated by flowing through a coil immersed in hot water using an RTE-210 NESLAB constant temperature water bath. Flow was equalized between the two lines using the air compressor regulators and inline cutoff valves. The flow rate and relative humidity was measured and determined for both lines. The airflow was measured using a VMM 402 Interface Associates flow meter. Dry-bulb temperatures were also measured at the inlet side of the valve. The ambient temperature and relative humidity are recorded before each run.

LABTECH software was used for data acquisition with wet-bulb, dry-bulb, and elapsed time data collected at 1000 Hz. The two inlet dry-bulb temperatures, relative humidity, and flow data were recorded at 0.5 Hz. The date, time, chamber or ambient temperature and humidity, and total flow at the outlet were recorded manually.

THERMOCOUPLES

Wet-bulb and dry-bulb thermocouples were installed 1 in. from the outlet port of the solenoid valve inside the Tygon tubing. These were constructed from type T 44AWG thermocouple wire with both negative (constantan) and positive (copper) leads under the same enamel insulation (Physitemp Instruments, Clifton, New Jersey, model W-TW-44P). Thermocouple tips were spot welded to create bead diameters of 0.05 mm using a HOTSPOT-TC weld manufactured by DCC Corporation.

The wet-bulb thermometers were a dry-bulb thermocouple with a wick covering the tip or measuring junction. The wick consists of 100% cotton string from nontreated, nonsterilized medical gauze tied around the tip of the thermocouple covering the bead. The cotton string was then trimmed to reduce mass to assure minimum response time. The number of the cotton fiber strands required to cover the bead will vary depending on the bead size. Braided cotton strands were also used to carry the water 1 cm or less from the end of the capillary tubing to the wick around the thermocouple bead. This assures that a water droplet is not formed around the thermocouple bead and yet the wick remains saturated with water. This technique ensures a continuous mass rate of flow of moisture input to the ambient air surrounding the wick at various ventilation rates. The average density of the wick saturated by distilled water was 1.007 g/cm^3. Figure A-3 depicts a wet-bulb thermocouple schematic with the wick surrounding the thermocouple bead.

Plastic capillary tubes were used to supply the wick with the water required to keep it moist. One end of TYGON plastic tubing (ID=0.01, OD=0.03) was submerged in a container of distilled water with the other end supplying the wick with moisture using the capillary action of the tube. The plastic tubing was primed initially by injecting water into the tubing using hypodermic needle to flush the line. Distilled water was used to ensure no film formation or adverse effects on surface properties of water or wicking material as reported by Harrison (reference 16). The water container was placed on a manual elevator and the flow of water to the wick controlled by raising and lowering the container. Each thermocouple was calibrated individually. The wet-bulb thermocouples were calibrated as dry-bulb thermocouples before wick was attached. A two point calibration (0°C, 29.7716°C) was conducted using an electric zero point cell (POND Engineering Laboratory, Inc.) and gallium cell (YSI Model 17402, Gallium Temperature Standard, Basic Meteology Yellow Springs Instrument Company).

EMPIRICAL TECHNIQUES

Independent variables affecting thermocouple response times in this experiment included the air velocity, temperature at which the air was heated, and direction of temperature change. These same variables were considered in an earlier study of dry-bulb thermocouple response times (reference 11).

The air velocity was selected at three levels. The upper flow limitation was dictated by the capacity of the wet-bulb thermocouple to withstand flow without losing or displacing the wick or thermocouple bending and touching the wall of the conduit. The velocities selected were 1.5, 2.0, and 2.5 m/sec. Flow regulator valves and in line shutoff valves were used to reach the desired flow rate and helped stabilize the pressure. The upper limit of the flow was bound by compressor capability and Tygon tubing capacity. Difficulty in regulating flow would occur at 1.5 m/sec as a result of different reservoir sizes on the compressors. The housing dimensions used were 1 and 1 5/16 in. The experimental runs were repeated for each of the housing dimensions.

Three bath temperatures were used (70°C, 80°C, and 90°C) to heat the air; the upper limit on the bath temperature without affecting the integrity of the Tygon tubing was 90°C. Small changes in temperature were considered in the study determining the time constant for the dry-bulb thermocouples (reference 11). It was found that time constants are more accurately

determined for smaller temperature changes rather than large changes because of the dependence of gas stream and thermocouple physical properties on temperature (reference 6). Small temperature differences within the conduits of the solenoid essentially eliminated the effects of radiation and conduction; consequently, the rate of heat gained or loss by the thermocouple as the flow changes from C-H or H-C is primarily resulted from forced convection. Negligible radiation effects justified omitting thermocouple shielding which optimized heat transfer between the gas stream and thermocouple tip. This resulted in high accuracy and repeatability in calculating the time constant of the thermocouple.

The third factor considered was the direction of which the temperature was changed. The first option was to expose the wet-bulb and dry-bulb thermocouples to the ambient flow first and then switch to the heated flow. The second option was to stabilize the system at the heated flow temperatures and then switch to the ambient or cooler flow. Both options were considered. The A/C current switch was turned on for the heated flow, which in turn caused the solenoid valve to heat. This problem was addressed by switching the inlet flow at the solenoid valve, which in turn allowed the valve to be at open position for the heated line when off. With the A/C power off the only heating inside the valve was directly as a result of the heated air and not the A/C current.

The time constants were calculated by first using Statistica software to find the range of time during which the change in temperature takes place. After the temperature before and after the change for both the dry-bulb and the wet-bulb were determined, the data were graphed and the initial and final temperatures were determined. The excess data were then filtered using Excel. SigmaPlot was then used to transform the data to mathematical equation. The equations, along with the data, were exported to TableCurve to calculate the time constants. The data were plotted on a semi-log graph and all points to the left of the inflection point were removed. The curve was fitted using a simple equation by maximizing the r^2.

The mathematical equations are in the form of "$\ln y = a + b\chi$". Determine the value of χ for the point along the line of data in the graph at which the Y-value is expressed in equation (1).

$$T_o - (\text{reference } (T_o - T_f) \times 0.632) = Y \qquad (1)$$

Time constant τ is then calculated by subtracting T_f from the new value for χ.

THEORETICAL ANALYSIS

The three heat exchange models were considered: (1) Ramp change - in which the temperature of the medium is increased in a linear fashion which in turn causes a linear increase in the thermocouple temperature; (2) Step change - in which the temperature of the medium is changed "instantaneously" causing a rapid change in the thermocouple temperature; (3) Periodic change - in which the temperature of the medium is changed sinusoidally causing alternate temperature changes in the thermocouple. The step change most closely models the response time of a fine dry-bulb thermocouple in air (reference 11).

This step change model of thermocouple temperature response considers first order response only. The finite time required to transfer the heat from the initial environment to the thermometer is known as the transient time. This period is considered an initial transient period before the thermocouple response could be characterized as first order. The first order response is an exponential curve (straight line on a semi log plot).

No instrument, however fast or sensitive, responds instantly to a change in its environment. Thus, thermocouples used to measure changing temperatures in a dynamic environment will not immediately indicate the true environmental temperature. This lag in thermocouple temperature response is the experimental thermocouple time constant or response time and corresponds with τ. Graphical solutions were used to quantify τ from experimental data.

The technique of Murdock et al. (reference 3) was used to identify thermocouple response time. Briefly, the initial thermocouple transient period was identified from the log linear portion of the response curve. Transforming temperature data as:

$$\text{Log T} = \left|1 - \frac{T_f}{T}\right| \tag{2}$$

where T = thermocouple temperature and T_f = final recorded thermocouple temperature, the temperature curve initially displays nonlinear behavior followed by a first order (linear) response.

To isolate the thermocouple linear response, initial nonlinear temperature response regions were omitted when calculating thermocouple response times in accordance with Murdock et al (reference 3). The inflection point (at time = t_0) marking the beginning of the exponential (log linear) portion of the curve was found. First order linear regression fit a line through this portion of data. Final temperature (steady state temperature of the conduit air stream) is first achieved at time t_f. Thermocouple response time represents 63.2% of the elapsed time from t_0 to t_f.

For the dry-bulb, the thermocouple response to an ambient temperature step change from $T_{amb,1}$ to $T_{amb,2}$ is normally described by:

$$T_{tc} = T_{amb,1} + \left(T_{amb,1} - T_{amb,2}\right) e^{-t/\tau} \tag{3}$$

where τ defines the time required for T_{tc} to reach 63.2% of the difference between $T_{amb,1}$ and $T_{amb,2}$. Solutions for τ can be accomplished either numerically or graphically. An empirical solution given by Scadron and Warshawsky (reference 8) for a time constant, τ_c, involving only convection is:

$$\tau_c = .302 \frac{\rho_w c_w D^{1.5}}{(Mp)^{0.5} T_t^{0.18}} \left(1 + 0.2M^2\right)^{0.25} \tag{4}$$

where $\rho_w c_w$ = product of the wire density and heat capacity, calculated for a thermocouple wire pair as the arithmetic mean of the thermocouple wire (copper, constantan) properties, D = wire diameter, p = atmospheric pressure, T_t = total temperature, and M = Mach number of gas flow. Average air stream temperature was used to determine thermal characteristics of air.

When considering wet-bulb thermocouples, capillary effect is not likely to be significant when the wick is thoroughly saturated with water and there is also evaporation cooling that is added to the equation. This additional factor influences the heat transfer characteristics of the system by providing faster cooling rate of the thermocouple when going from hot to a cold flow and slower heating rate when going from a C-H flow. The wet-bulb influences the time constant for the response of each thermocouple. The evaporative cooling is a function of the degree of saturation at the wick. Considering that no water droplet is formed around the tip/wick and that the density of the saturated wick (1.007 g/cm^3) is very close to the density of water, the assumption that a thin film of water covers the tip of the thermocouple is valid. The increased response time as a result of heat transfer through the water film is characterized by Murdock (reference 3) for all liquid films to be:

$$\tau_{wb} = \frac{1800 \rho_w c r_f}{h_f} \tag{5}$$

where ρ_w is density of water in lb per cubic feet, c is specific heat in Btu per lb-F, r_f is radius or thickness of the film in feet, h_f is the film heat transfer coefficient in Btu per hr-ft sq-f. Considering that equation (5) is the response time as a result of heat transfer through a liquid film with a thickness of $r_f = r_w - r_{tc}$ where r_w is the radius of water droplet and r_{tc} is the radius of thermocouple.

To analyze the process of mass transfer as a result of evaporation from the thin film of water covering the tip, simultaneous heat and mass transfer (low rate) is considered. The latent heat is absorbed when vapor is created and the surface is cooled lowering the vapor pressure and consequently reducing evaporation rate. Lienhard and Lienhard (reference 18) modeled the low rate of heat and mass transfer as a result of evaporation from a thin film at low temperatures using sling psychrometers. Writing the energy balance on the wick:

$$n_{H_2o,s} H_{H_2o,s} - q_s = n_{H_2o,u} H_{H_2o,u} \tag{6}$$

i.e.,

Enthalpy of the water vapor leaving the surface	-	Heat convected to wet-bulb	=	Enthalpy of liquid water arriving

Where n_{H_2o} is number of moles of water transferred. Since $n_{H_2o,s} = n_{H_2o,u}$ and enthalpy change result from vaporization, $H_{H_2o,s} - H_{H_2o,u} = H_{fg}$, hence

$$n_{H_2o,s} H_{fg}\Big|_{wb} = h(T_a - T_{wb}) \tag{7}$$

where H_{fg} is the heat of vaporization. At low rate of flow, $n_{H_2o,s} \cong j_{H_2o,s}$ and in terms of mass transfer coefficient

$$g_{m,H_2o}\left(m_{H_2o,s} - m_{H_2o,a}\right)H_{fg}\Big|_{T_{wb}} = h(T_a - T_{wb}) \tag{8}$$

The heat transfer coefficient for the forced convection has the general form

$$\frac{hD}{k} = cR^{1/2}\,\mathrm{Pr}^{1/3} \tag{9}$$

but

$$\frac{g_m}{h} = \frac{1}{c_p Le^{2/3}} \tag{10}$$

and

$$\frac{h}{g_m c_p} = Le^{2/3} \tag{11}$$

This ratio depends primarily on dry-bulb air temperature, T_a and humidity of ambient air, $m_{H_2o,a}$.

A source of error in measuring response time, τ with wet-bulb thermocouples is the water film thickness (the amount of moisture or dew on the wick). The wick could actually accumulate a large drop of dew or water on the tip of the thermocouple that would then insulate the bead from the flow. Other sources of error in computing τ can be attributed to conduction, radiation, and velocity effects during temperature measurements. Conduction occurs along both the positive and negative thermocouple leads. Heat also radiates from the conduit walls to the thermocouple when going from C-H chamber and from the thermocouple to the surrounding surfaces when going from H-C media. Assuming the mass of the wire insulation is sufficient to keep support temperature relatively constant, then one can define a time constant, $\tau_{k,r,c}$, accounting for convection, conduction, and radiation (reference 7) as:

$$\tau_{k,r,c} = \frac{\tau_c(1-\psi_w)}{1+\dfrac{4\beta\varepsilon_w}{T_g}} \tag{12}$$

where ψ_w = conduction correction factor, β = radiation error factor, ε_w = thermocouple emissivity, and T_g = gas temperature (reference 2). Both ψ_m and β are defined by Scadron and Warshawsky (reference 8) in terms of gas and wire properties and the gas stream Mach number and are .008 and 1.275, respectively, for the conditions used in this study. Applying these values to equation (11) demonstrates that calculated differences between τ_c and $\tau_{k,r,c}$ are negligible (<5%) given the present study conditions. Kinetic energy effects on temperature sensing attributable to gas stream velocity are also negligible at low Mach numbers (reference 8).

An energy balance between convective heat transfer and heat accumulation in the tip for this ideal system is given by:

$$h_{eff} A(T_a - T_{tc}) = m_{eff} c_{eff} \frac{dT_{tc}}{dt} \tag{14}$$

where h_{eff} = effective convective heat transfer coefficient of liquid film held by wick surrounding the bead, A = outer surface area of the system, T_a = ambient environmental temperature, and T_{tc} = thermocouple temperature, m_{eff} and c_{eff} represent the combined mass of the bead, wick, and liquid film and effective heat capacity of this system, respectively. Redefining thermocouple density and mass as:

$$\rho_{eff} = \frac{m_{eff}}{V_{therm}} \tag{15}$$

$$m_{eff} c_{eff} = m_w c_w + m_b c_b \tag{16}$$

and the thermocouple time constant, τ as:

$$\tau = \frac{m_{eff} c_{eff}}{h_{eff} A} \tag{17}$$

the effective heat transfer coefficient is given by:

$$h_{eff} = h_D \rho_w c_p \left(\frac{Sc}{\mathrm{Pr}}\right)^{2/3} \tag{18}$$

where $h_D = f/2$, ρ_w and c_p are the density and specific heat of water, Sc is the Schmidt number, Pr is the Prandtl number, and f is the friction factor for flow of air over the film which is given by:

$$f = \frac{0.184}{\mathrm{Re}_D^{0.2}} \tag{19}$$

STATISTICAL ANALYSIS

A paired-t test was used to assess whether the housing dimension, ambient temperature and relative humidity, bath temperature, air flow velocity, and the direction of temperature change (H-C versus C-H) affected response times. Correlation analysis and a one-way analysis of variance identified which independent variables significantly affected thermocouple response times. Significance was measured at a significance level (α) = 0.05. Uncertainty as a function of systematic bias, B, and experimental standard error of the mean, $S_{\overline{X}}$, was determined from:

$$U_{RSS} = \left[B^2 + \left(t_{95} S_{\overline{X}}\right)^2\right]^5 \qquad (20)$$

where t_{95} = Student t statistic for a normal distribution at a 95% degree of confidence (reference 7). It was assumed that B represented the temporal resolution of the data acquisition system that equaled 1 msec for a 1 kHz sample rate.

RESULTS

Figure A-4 depicts a typical response of a wet-bulb thermocouple as the flow is switched from hot-to-cold. Fifty-four runs were made at random with the sequence specified by the methods for a total of 108 runs. Tables 3 and 4 show the experimental data and the response times for both the dry-bulb and wet-bulb thermocouples using two different housing inside diameter.

The last two columns in tables 3 and 4 provide calculated time constants (response times) for each run. No significant difference was found between response times based on the two housing sizes used in the experiment based on a paired-t test at $\Delta<0.05$. Mean overall response time using 1 5/16 in. housing for the dry-bulb was 72.3 ± 12.9 msec and for the wet-bulb 152.5 ± 50.3 msec. Mean overall response time using 1 in. housing for the dry-bulb was 69.9 ± 9.9 msec and for the wet-bulb 175.0 ± 63.9 msec.

The regression summary for the wet-bulb response times is as follows:

Dependent Variable: DB TC (Dry-Bulb Time Constant) $r= 0.49$ $r^2= 0.24$
Adjusted $r^2= 0.22$, $F(3,104)=11.066$ $p<.00000$ Std. Error of estimate: 10.169.

N=108	Beta	Std. Err.	B	Std. Err.	t(104)	p-level
Intercept			107.3333	11.15704	9.62023	0.000000
Air Vel	-0.106855	0.085374	-3.0000	2.39692	-1.25161	0.213521
Bath Temp	-0.127632	0.085374	-0.1792	0.11985	-1.49498	0.137949
Flow Dir	-0.462891	0.085374	-10.6111	1.95708	-5.42192	0.000000

The regression summary for the dry-bulb response times is as follows:

Dependent Variable: WB TC (Wet-Bulb Time Constant) $r= 0.24$ $r^2= 0.056$
Adjusted $r^2= 0.029$, $F(3,104)=2.0552$ $p<.11072$ Std. Error of estimate: 1901.1.

N=108	Beta	Std. Err.	B	Std. Err.	t(104)	p-level
Intercept			-108.907	2085.715	-0.05222	0.958457
Air Vel	-0.185127	0.095275	-870.667	448.083	-1.94309	0.054709
Bath Temp	0.115149	0.095275	27.078	22.404	1.20860	0.229556
Flow Dir	-0.091844	0.095275	-352.685	365.859	-0.96399	0.337285

Table 3: Response Time Data and Experimental Results (Housing ID = 1 5/16 in.)

Run No.	V_{air} (m/sec)	T_{Bath} (°C)	Flow Dir	T_{amb} (°C)	RH_{amb} (%)	DB Ti (°C)	DB Tf (°C)	WB Ti (°C)	WB Tf (°C)	DB TC (msec)	WB TC (msec)
1 – 3	2.00	70	C - H	27.1	38	27.01	28.17	13.39	13.82	74	136
4 – 6	2.00	70	H - C	27.1	38	31.24	29.76	15.28	14.77	61	120
7 – 9	2.50	70	H - C	27.3	37	33.36	31.07	16.06	15.78	73	107
10 - 12	2.50	70	C - H	27.6	37	28.79	29.96	14.18	14.52	78	219
13 - 15	1.50	70	C - H	27.9	37	27.75	28.63	12.69	13.06	82	150
16 - 18	1.50	70	H - C	28.0	37	30.03	29.30	13.83	13.62	66	187
19 - 21	2.00	80	H - C	28.2	38	30.87	29.17	13.61	13.18	65	232
22 - 24	2.00	80	C - H	28.2	38	28.00	29.78	12.31	13.01	88	170
25 - 27	2.50	80	C - H	28.2	38	27.68	30.18	12.50	12.67	63	110
28 - 30	2.50	80	H - C	28.5	39	33.25	30.82	16.03	15.58	60	95
31 - 33	1.50	80	H - C	28.5	40	32.65	31.36	16.32	15.99	60	105
34 - 36	1.50	80	C - H	28.5	40	29.22	30.55	14.16	14.91	80	204
37 - 39	2.00	90	C - H	28.5	39	27.59	28.91	12.93	13.62	78	173
40 - 42	2.00	90	H - C	28.6	39	34.21	31.66	16.35	14.97	64	127
43 - 45	2.50	90	H - C	28.7	39	39.03	35.13	18.08	17.34	72	129
46 - 48	2.50	90	C - H	28.8	39	31.86	33.92	14.55	17.16	86	206
49 - 51	1.50	90	C - H	28.8	39	30.14	32.01	15.04	15.70	78	128
52 - 54	1.50	90	H - C	28.8	39	35.69	33.43	17.46	16.52	72	145
Mean				28.2	38.5	31.0	30.8	14.7	14.8	72.3	152.5
Standard Deviation				0.563	0.955	3.228	1.923	1.710	1.453	12.910	50.369

Table 4: Response Time Data and Experimental Results (Housing ID = 1 in.)

Run No.	V_{air} (m/sec)	T_{Bath} (°C)	Flow Dir	T_{amb} (°C)	RH_{amb} (%)	DB Ti (°C)	DB Tf (°C)	WB Ti (°C)	WB Tf (°C)	DB TC (msec)	WB TC (msec)
1 - 3	2.00	70	C - H	27.2	40	26.33	27.36	11.64	11.80	85	199
4 - 6	2.00	70	H - C	27.1	40	31.56	29.37	13.84	13.35	71	182
7 - 9	2.50	70	H - C	27.2	36	34.54	31.18	15.06	14.68	62	223
10 - 12	2.50	70	C - H	27.3	40	29.43	31.89	13.74	15.77	84	206
13 - 15	1.50	70	C - H	27.3	40	28.94	30.33	14.28	15.42	91	214
16 - 18	1.50	70	H - C	27.3	40	31.63	30.22	15.74	15.31	68	229
19 - 21	2.00	80	H - C	27.5	39	31.56	29.19	14.86	13.84	66	227
22 - 24	2.00	80	C - H	27.6	39	28.70	30.29	13.01	14.78	64	179
25 - 27	2.50	80	C - H	27.6	39	28.80	31.57	13.05	15.75	66	153
28 - 30	2.50	80	H - C	27.8	39	36.54	32.42	16.35	16.21	64	143
31 - 33	1.50	80	H - C	27.9	39	35.07	32.29	16.23	16.09	64	133
34 - 36	1.50	80	C - H	27.9	39	30.37	31.54	14.44	14.66	70	111
37 - 39	2.00	90	C - H	28.0	39	27.85	29.59	12.78	13.15	67	111
40 - 42	2.00	90	H - C	28.0	39	34.45	31.64	15.73	15.50	59	119
43 - 45	2.50	90	H - C	28.1	39	37.96	33.70	16.89	16.79	64	104
46 - 48	2.50	90	C - H	28.2	39	31.06	34.64	14.04	15.06	68	127
49 - 51	1.50	90	C - H	28.2	38	30.33	32.63	14.44	15.53	74	169
52 - 54	1.50	90	H - C	28.3	38	34.65	32.53	16.40	15.54	73	326
Mean				27.7	38.9	31.7	31.2	14.6	15.0	69.9	175.0
Standard Deviation				0.393	1.377	3.206	1.775	1.457	1.251	9.906	63.922

Based on the data collected, as the bath temperature increases, the wet-bulb response time decreases for the C-H flow. No significant change in wet-bulb response time is observed for H-C flow. Figure A-5 shows the average wet-bulb response time for housing air flow velocity of 0.276 m/sec plotted for the three bath temperatures. Marked correlations are significant at $P<0.05$ between air flow velocity and wet-bulb thermocouple response times. On the basis of the results obtained from this study, there is a positive correlation between air velocity and response time for both dry-bulb and wet-bulb thermocouples, as was the case in earlier study (reference 11).

No significant changes in response times were observed as a result of bath temperature changes from 70°C to 90°C for either wet-bulb or dry-bulb. Figures A-6, A-7, and A-8 show the mean response times plotted for the different bath temperature and directional flow for the wet-bulb and dry-bulb thermocouples, respectively. Response times were generally larger when heating – going from C-H for the dry-bulb only. No such trend is identified in case of the wet-bulb.

Positive correlation was found for the wet-bulb response times as a function of flow direction (correlation coefficient $r = 0.22$). Larger values of response times were observed at flow direction hot-to-cold. The same correlation was found to be negative for dry-bulb response times with larger values of response times observed at C-H flow direction correlation coefficient $r = -0.48$).

Figure A-9 shows the mean dry-bulb and wet-bulb response times for both flow directions as a function of velocity. Larger variations in wet-bulb response times are generally observed with the largest variations for flow direction from hot-to-cold. Figure A-10 shows the wet-bulb and dry-bulb time constants as a function of air velocities for both directional flows. Based on the data platted, which is categorized by changing the flow from H-C and C-H, it can be stated that the impact of the change in flow has a more profound impact on the dry-bulb than it does the wet-bulb. Cooling the sensor responds more rapidly than heating the sensor.

DISCUSSION

Many have attempted to quantify or measure the response time of a temperature measuring device or system using theoretical or experimental techniques such as submersion of the bulb or the thermocouple. However, no one appears to have developed an analogous technique for a wet-bulb thermocouple. Without an accurate and repeatable procedure in measuring and characterizing the response times of wet-bulb thermocouples, the response time of the data collection system is irrelevant. This study demonstrates a technique for easily characterizing the response time of the entire data collection system which uses both dry-bulb and wet-bulb thermocouples.

The technique reported above provides a simple and repeatable method for empirically quantifying fine dry-bulb and wet-bulb thermocouple response times in air. Mean response times determined in the present study for the dry-bulb is 0.071 sec which is comparable to those previously measured for 44 AWG thermocouples (0.055 sec) at air flow velocities of (3.1 – 3.7 m sec^{-1}) (reference 11) and (0.035 sec) at comparable air velocities (3.4 – 5.5 m sec^{-1}) (reference 9).

Humidity sensors or measuring devices are usually one of the following: dew-point hygrometers, psychrometers, sorption sensors, or traditional thin film sensors which are considered to have relatively short response time usually less than 1 min as reported by Berlicki (reference 12). The main disadvantages of this type of sensors used to measure wet-bulb temperatures is still the slow response times which is directly a function of the sensor mass, the thickness of the film, and the sensitivity of the sensor to the environmental conditions. Repeatability problems could also arise from inconsistencies in level of the moisture on the film since the sensor is wetted before each run.

In the past, there were few other attempts in measuring relative humidity using dry and wet-bulb sensors or thermocouples. Even now the latest techniques in measurement of relative humidity using thin film requires extended time for measurement, where as the proposed technique in this study is designed for fast measurement of relative humidity in an environment such as respiratory track where humidity is continuously changing in small time intervals. Mean response times for wet-bulb in the present study are 0.164 sec.

For the most part, measuring response times in air included only the dry-bulb. Carbon, et al. (reference 9) used a sliding metal shutter to control airflow across a thermocouple tip. Berlicki et al (reference 12) developed a relative humidity sensor using thin film approach as classically described by dry and wet thermometers. The sensor used thermopiles covered with wet tissue. In such a case, the sensitivity of the sensor is dependent on the film thickness. Control of the liquid film in measuring wet-bulb has always been a challenge.

Attempts to develop an equivalent system for the present study using rapid response solenoid valves (ARO Fluid Power Products, Bryan, OH, model CAT33P) produced unreliable results. Earlier study (reference 11) attempted to ameliorate these problems by moving the thermocouple between two relatively large thermally stable media. Consequently, thermal perturbations caused by a step change were minor compared to redirecting airflows. In the

current study, rather than physically moving the thermocouples from one layer of flow to the other, the flow is toggled and the sensor is stationary. One of the problems encountered was the heating of the manifold when initially heated air was flown through it. The effect was minimized by minimizing the duration of the flow to a few seconds. The flow was switched as soon as it was stabilized. Another problem encountered was the heating of the manifold when the valve was initially set at energized status (AC current on) before switching. To avoid this problem, the valve was kept at deenergized state at all times and the lines were switched for various experimental runs.

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CONCLUSIONS

In summary, this approach appears suitable for measuring wet-bulb response times for a large range of temperatures and conduit ΔT's but at lower flow rates. Higher flow rates contribute to drying or displacing the wet-bulb wick. Study results indicate this technique produces repeatable and reliable results when characterizing the response times of a temperature data collection system using both wet-bulb and dry-bulb thermocouples. Furthermore, modifying this apparatus allows this system to be used with gases other than air. This experimental approach eliminates reliance on manufacturers' estimates of thermocouple time responses and provides investigators the ability to quantify overall temperature measurement system responses.

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REFERENCES

1. P. Webb, Air Temperatures in Respiratory Tracts of Resting Subjects in Cold, J. Applied Physiology, vol. 4, pp. 378-382, 1951.

2. D.W. Ray, E.P. Ingenito, M. Sterk, P.T. Schumacker, and J. Solway, Longitudinal Distribution of Canine Respiratory Heat and Water Exchange, Journal of Applied Physiology, vol. 66, pp. 2788 – 2798, 1989.

3. J. W. Murdock, C. J. Foltz, and C. Gregory, A Practical Method of Determining Response Time of Thermometers in Liquid Baths, ASME Trans., Journal of Engineering for Power, pp. 27-32, Jan 1963.

4. ASTM, "Manual on the Use of Thermocouple in Temperature Measurement", American Society for Testing and Materials publication 470A, 1974.

5. OMEGA, The Temperature Handbook, Vol. 28, p. A-8.

6. A. F. Wormser, Experimental Determination of Thermocouple Time Constants with Use of a Variable Turbulence, Variable Density Wind Tunnel, and the Analytic Evaluation of Conduction, Radiation, and Other Secondary Effects, Society of Automotive Engineers Transaction, 5-8 Apr 1960.

7. R.P. Benedict, Fundamentals of Temperature, Pressure, and Flow Measurements, 3rd ed., John Wiley & Sons, New York, pp. 172-281, 1984.

8. M.D. Scadron and I. Warshawsky, Experimental determination of time constants and Nusselt numbers for bare-wire thermocouples in high-velocity air streams and analytic approximation of conduction and radiation errors. National Advisory Committee for Aeronautics, Technical Note 2599, Cleveland, Ohio, Jan 1952.

9. M.D. Scadron, Time Response Characteristics of Temperature Sensors. Aero Research Instrument Company Inc., Presented at SAE National Aeronautic Meeting, New York, NY, Apr 1960.

10. M.W. Carbon, H.J. Kutsch, and G.A Hawkins, The Response of Thermocouple to Rapid Gas-Temperature Change, Trans. ASME, vol. 72, pp. 655-657, 1950.

11. K. Farahmand, and J.W. Kaufman, Experimental Measurement of Fine Thermocouple Response Time in Air, Experimental Heat Transfer, 14:107-118, 2001.

12. J.W. Kaufman, G.K. Askew, and K. Farahmand, Apparatus for Obtaining Temperature and Humidity Measurements, US Patent Number: 6659963, 9 Dec 2003.

13. T.M. Berlicki, E. Murawski, M. Muszynski, S.J. Osadnick, and E.L. Prociow, Thermoelemnt Humidity Sensor, Sensor and Actuators, A 64 (1998) 213-217.

14. L.P. Harrison, Proposal for an Experimental Triple-Tubed Adiabatic Saturator to Measure Thermodynamic Wet-Bulb Temperature as a Limit Approach During the Saturation Process, U.S. Weather Bureau, Washington, D.C., Humidity and Moisture, Measurement and Control in Science and Industry, V 1, 33-63.

15. L.P. Harrison, Some Fundamental Considerations Regarding Psychrometry, U.S. Weather Bureau, Washington, D.C., Humidity and Moisture, Measurement and Control in Science and Industry, V 3, 71-103.

16. L.P. Harrison, Fundamental Concept and Definitions Relating to Humidity, U.S. Weather Bureau, Washington, D.C., Humidity and Moisture, Measurement and Control in Science and Industry, V 3, 3-69.

17. W.M. Rohsenow, H. Choi, Heat, Mass, and Momentum Transfer, Prentice Hall, 1961.

18. J.H. Lienhard and J.H. Lienhard, A heat Transfer Text Book, 3rd edition, web.mit.edu/lienhard/www/ahtt.html, 2000-2004.

APPENDIX A
FIGURES

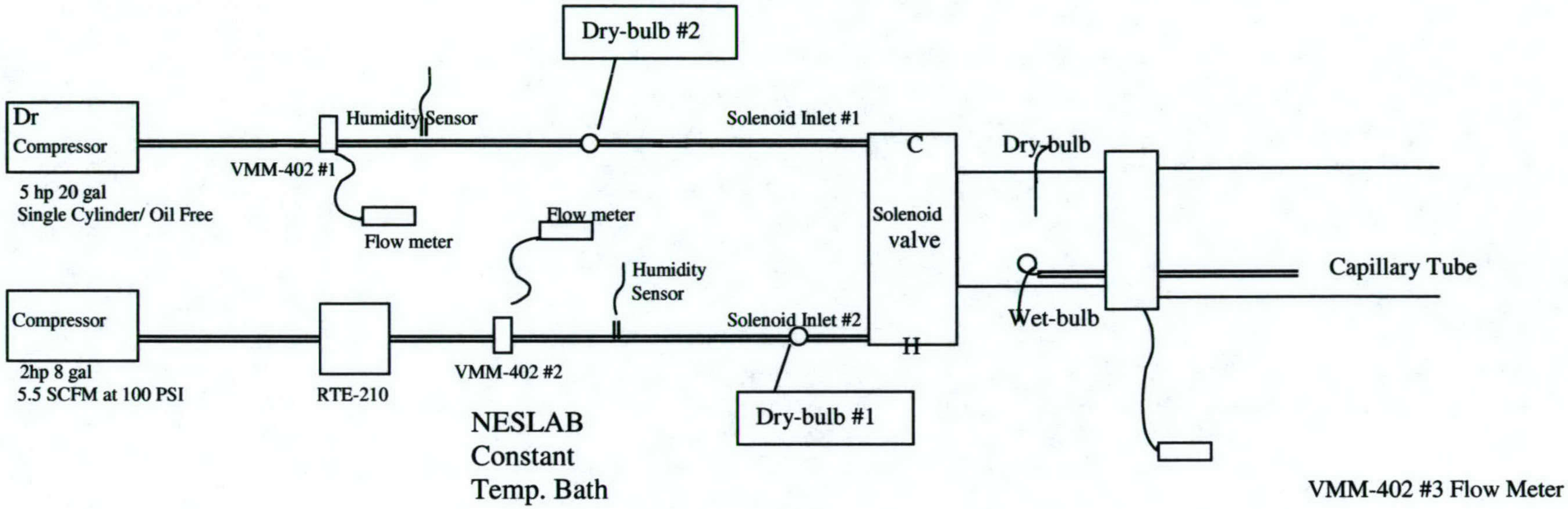


Figure A-1: Diagram of the Experimental Setup

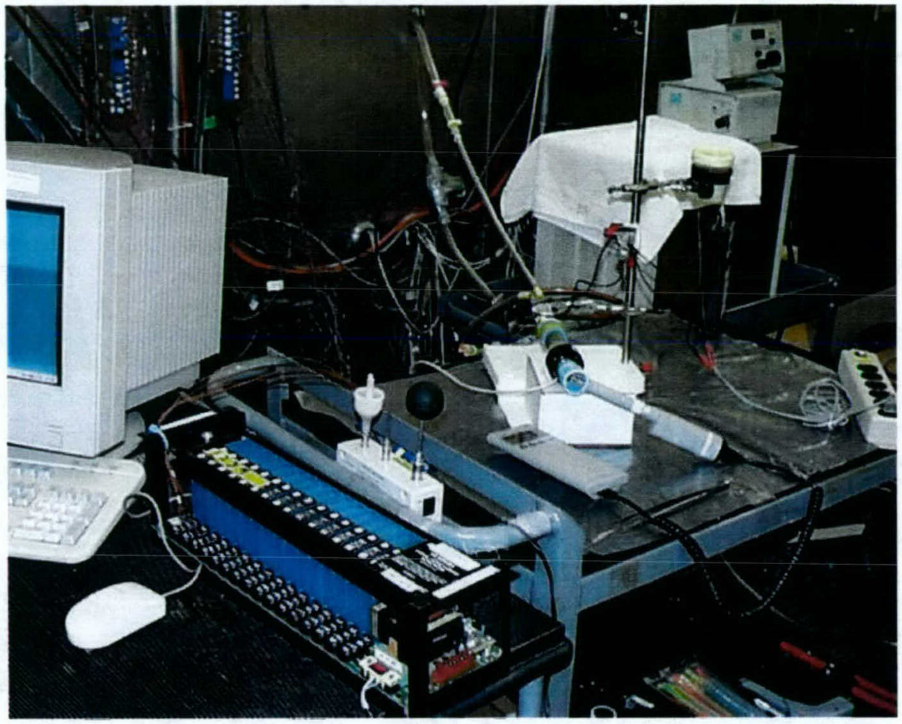
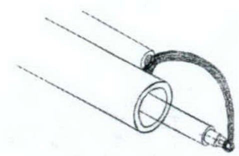


Figure A-2: Experimental Setup

Drawing Guide



1. 44 AWG thermocouple wires
2. Capillary tubing
3. Wet-bulb cotton wick
4. Cotton strands between the wick and capillary tube
5. Copper (copper), positive lead
6. Constantan (copper + nickel) wire, negative lead
7. Thermocouple bead

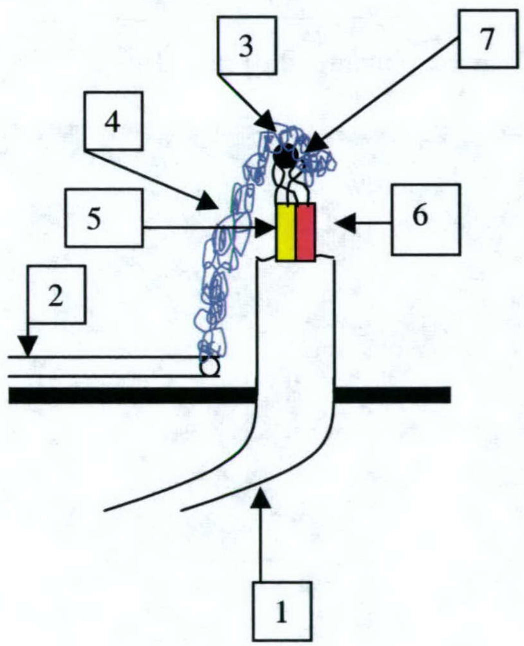


Figure A-3: Schematic Drawing of the Wet-Bulb Thermocouple

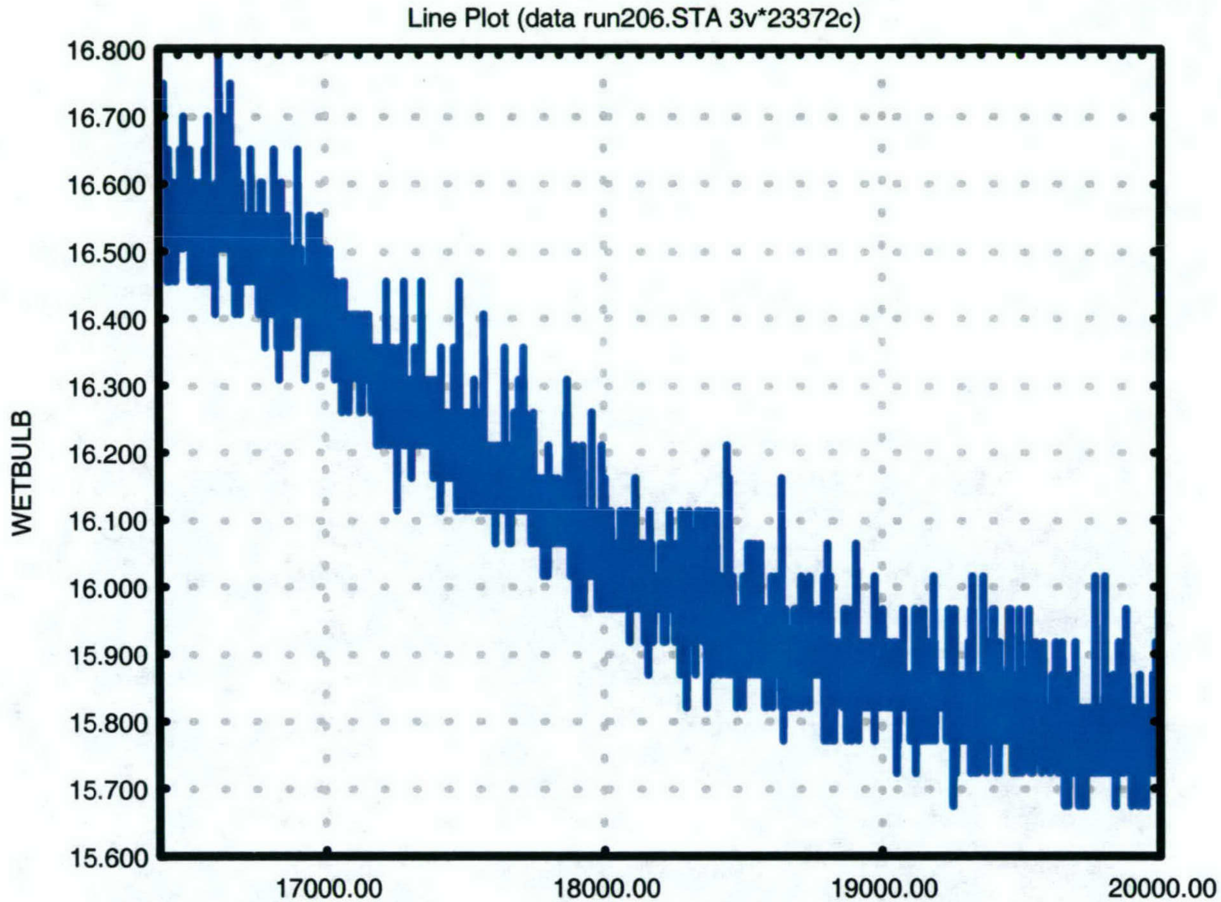


Figure A-4: Typical Response of a Thermocouple

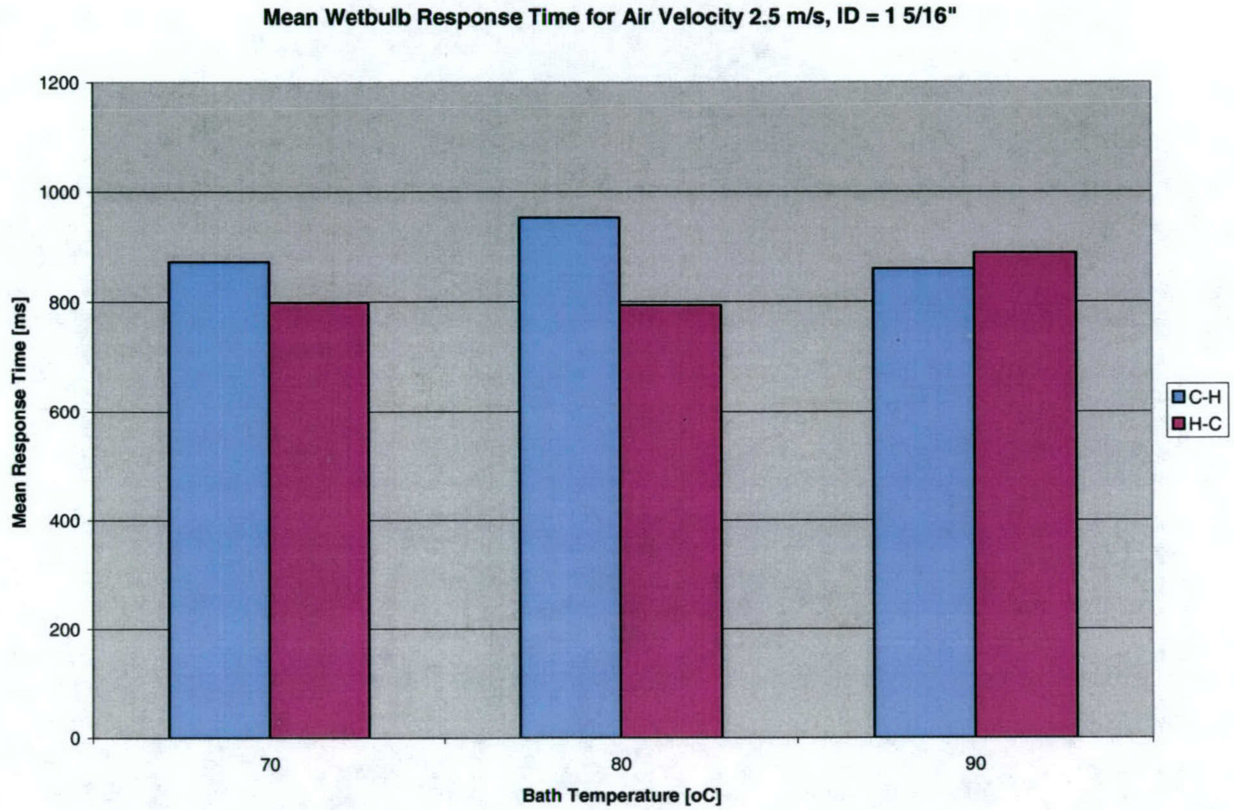


Figure A-5: Mean Wet-Bulb Time Constant for Velocity = 2.5 m/sec, ID = 1 5/16 in.

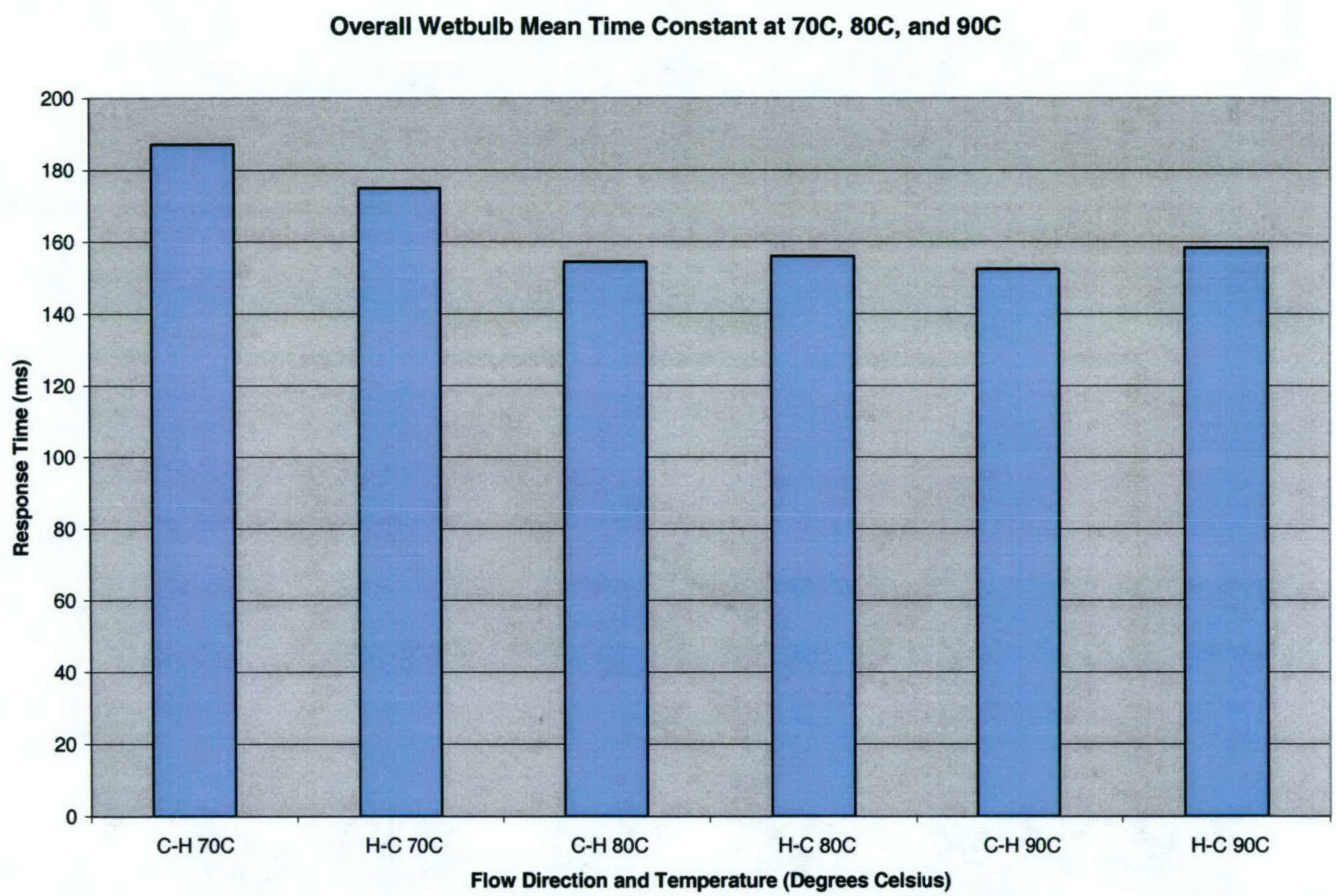


Figure A-6: Mean Wet-Bulb Response Times

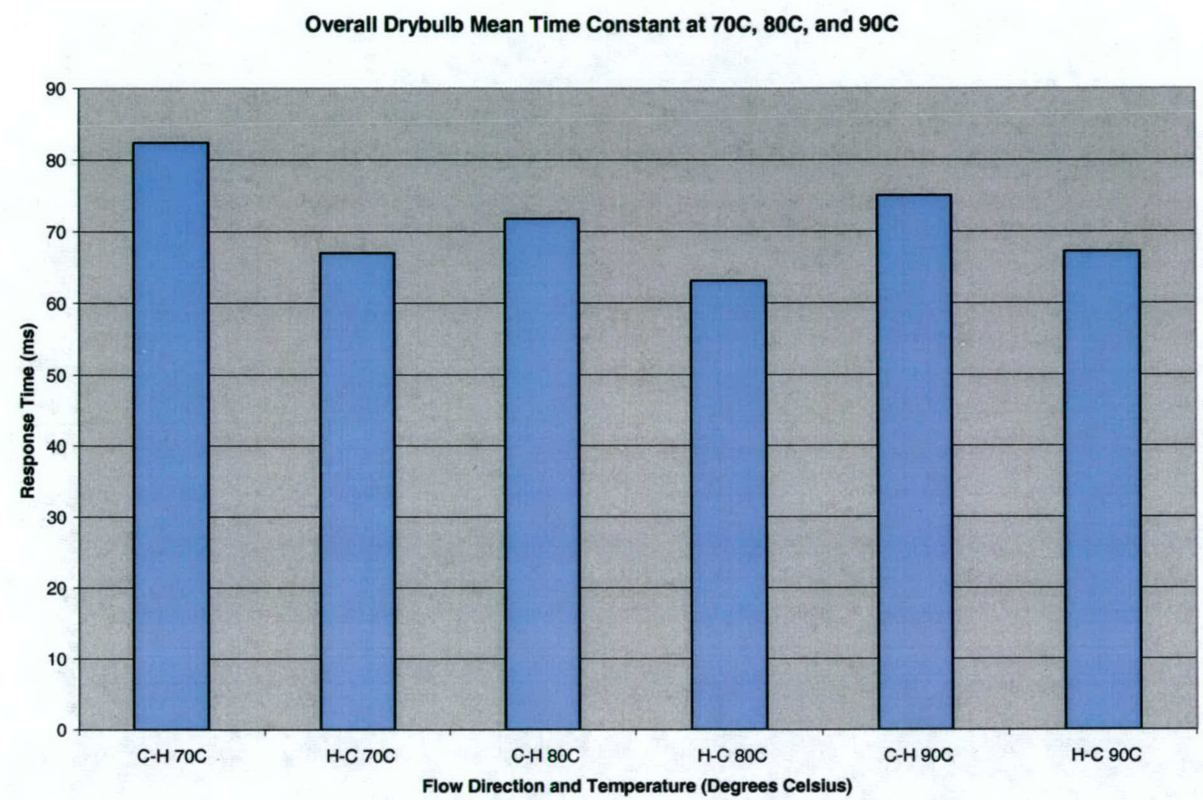


Figure A-7: Mean Dry-Bulb Response Times

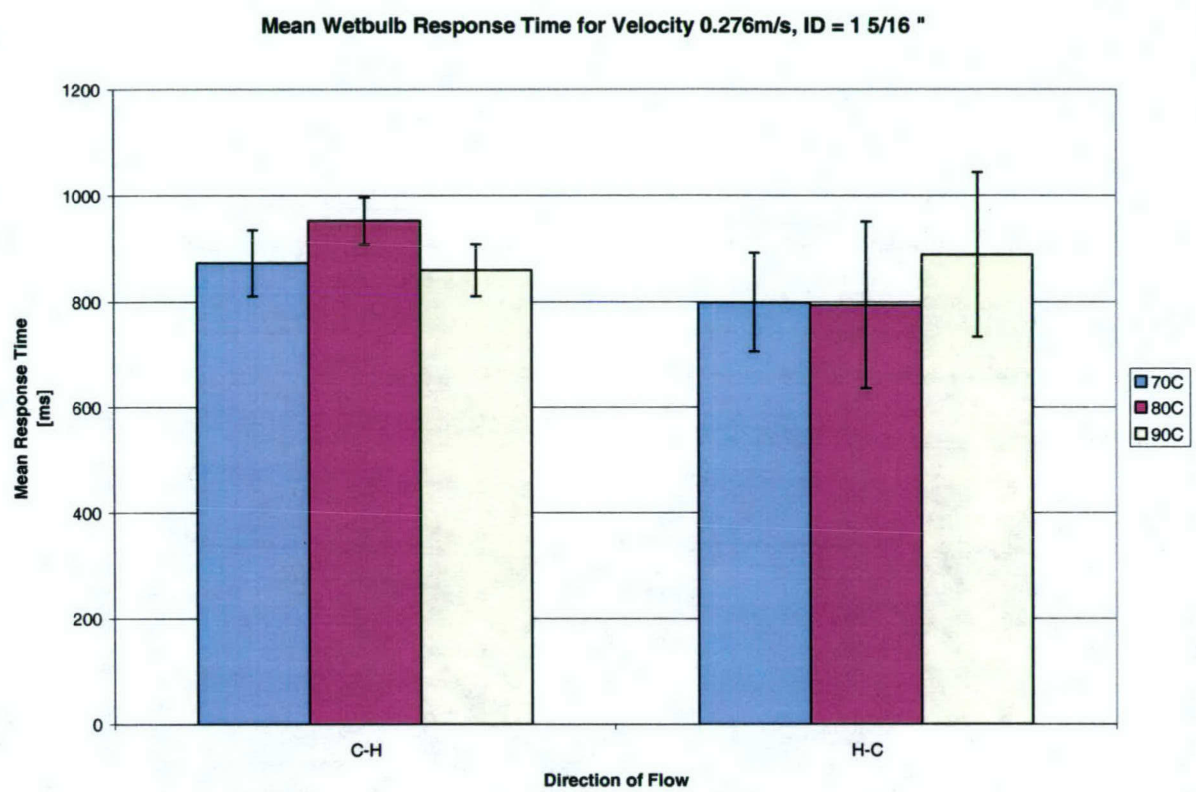


Figure A-8: Mean Wet-Bulb Response Times

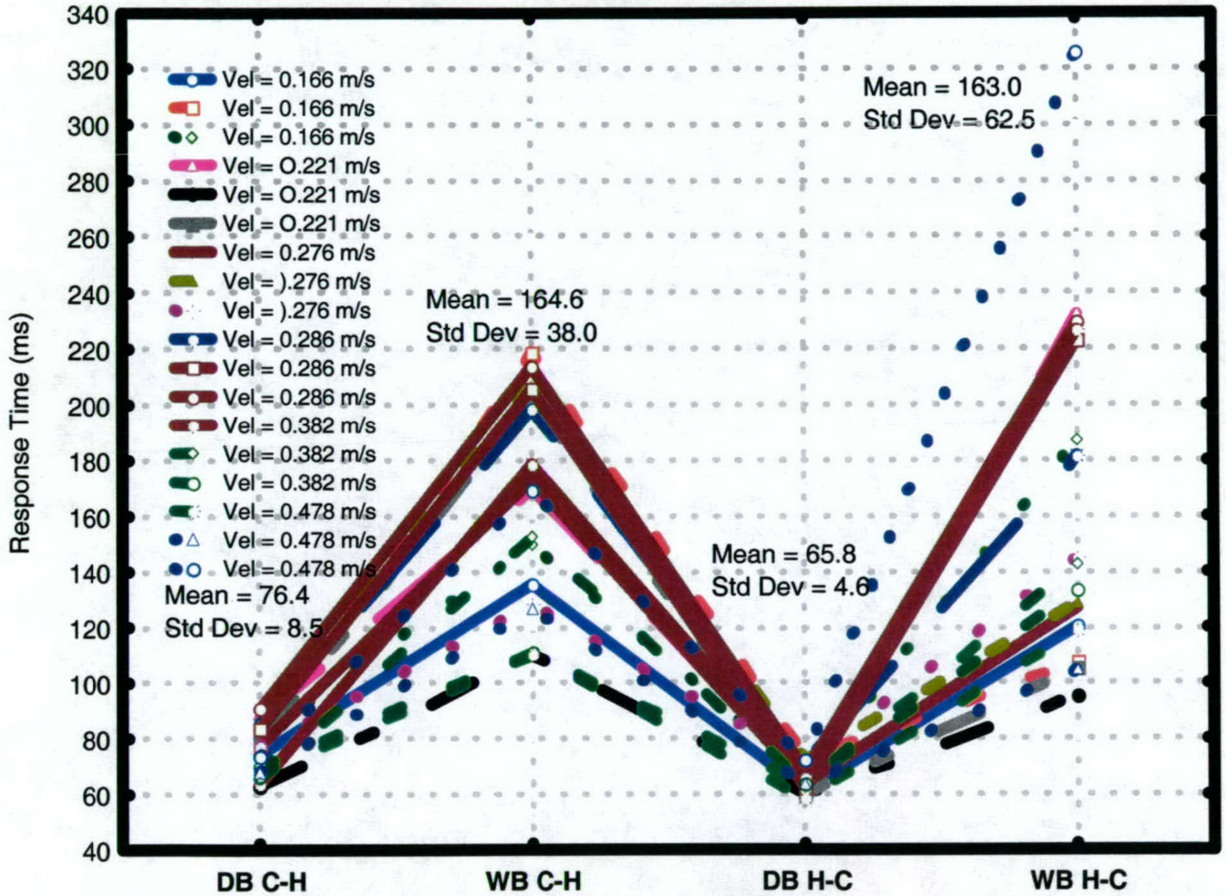


Figure A-9: Mean Dry-Bulb (DB) and Wet-Bulb (WB) Response Times

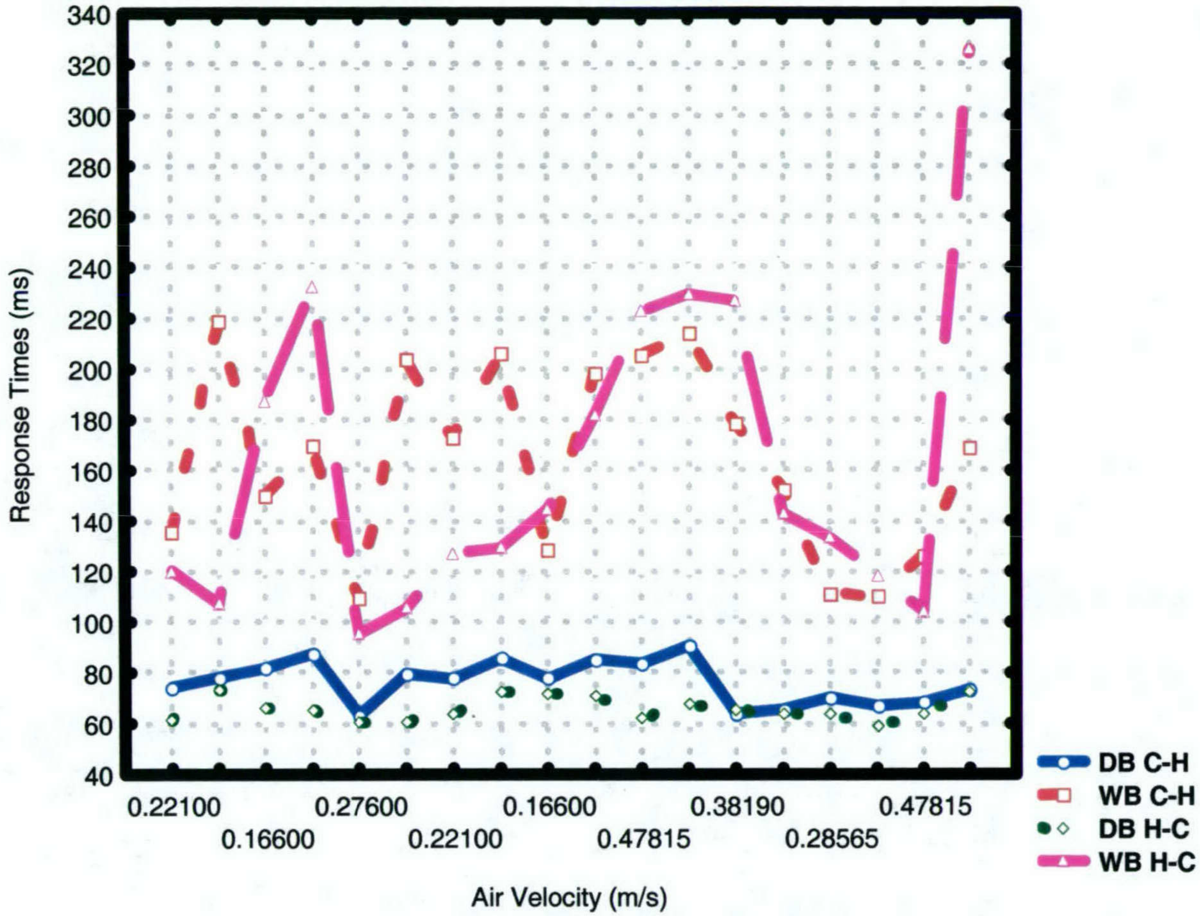


Figure A-10: Response Times as a Function of Air Velocity

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